Analysis Tools for MesonEx at CLAS12
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Overview

MesonEx
(also Carlos talk)

HASPECT

Data Handling Software

Longitudinal Plots

Likelihood Analysis
Enhance equipment in existing halls

Beam Power: 1 MW
Beam Current: 90 µA
Max Pass energy: 2.2 GeV
Max Energy Hall A-C: 10.9 GeV
Max Energy Hall D: 12 GeV
Primary Physics Goal for CLAS12 e- beam
  • Nucleon Structure (not discussed here)
  • But high potential for Meson spectro. (see also Hall D GLUEX)

• Strategy:
  • High Intensity electron Beam
    • Tag quasi-real photons
  • Large Acceptance Magnetic Spectrometer
  • Many final states
  • Linearly polarised photons
  • Amplitude analysis sensitive to small contributions
    • Close interplay of exp - theory
HASPECT

International collaboration preparing for MesonEx at CLAS12

Implement reliable amplitudes
Revisit techniques from earlier efforts
Accessible to all
Common Tools e.g IU AMPTOOLS
Work closely with JPAC

Frequent meetings and Workshops
HASPECT weekly meetings with experimentalists and JPAC
HASPECT weeks with guests from other projects
ATHOS Amplitude Analysis Workshops

Apply/develop with existing CLAS data
\( \gamma p \rightarrow N \pi \pi \quad \gamma p \rightarrow N K K \quad \gamma p \rightarrow N \eta \)
\( \pi \gamma p \rightarrow N \omega \quad \gamma p \rightarrow N \pi \pi \pi \quad \gamma p \rightarrow N \eta \pi \pi \)
\( \gamma p \rightarrow N \pi^+ \pi^- K^+ \)
\( \gamma p \rightarrow N \phi \pi \quad \gamma p \rightarrow N \phi \eta \quad \gamma p \rightarrow N \).....

Theoretical support:
A. Szczepaniak (IU/JPAC), V. Mathieu (IU),
E. Santopinto (INFN-GE), A. Vassallo (GE),
J. Ferretti (UMAS)

Experimental Analysis:
M. Battaglieri, R. deVita, A. Celentano,
S. Fegan (INFN-GE), A. Filippi (INFN-TO),
D. Glazier (Glasgow), S. Hughes (Edinburgh),
K. Hicks (OhioU), S. Lombardo (Cornell),
A. Rizzo (RomaTV), I. Stankovich (Edinburgh),
L. Zana (Edinburgh)
Use of Software in hadron physics

- Experimental Data
- Simulated Data
- Simulation
- Event Generator
- Particle Reconstruction
- Event Reconstruction
- Physics Analysis

Flowchart explaining the process from experimental and simulated data to physics analysis through stages of reconstruction and simulation.
Use of Software in hadron physics

Experimental Data

Statistical Methods

Particle Reconstruction

Event Reconstruction

Physics Analysis

Simulated Data

HASPECT Activity

Simulation

This talk

Event Generator

IU AmpTools JPAC (Vincent)
HASPECT Event Reconstruction

Provide code to handle routine tasks allowing procedures to become standardised
   Input/Output/Interfacing
   Histogramming
   Particle/reaction identification
   Event weighting

Maintain normal ROOT flexability for users

Users shift to physics and systematic studies

Promote full potential of ROOT
   Based on TSelector Tree analysis class
   Use of TEntryList class to prevent duplicating data
   ROOT system takes care of compilation and configuration
   Parallel ROOT Facility (PROOF)
   Statistical Analysis Packages (RooFit/Stats)

https://github.com/HASPECT/Events
Example Analysis
Each step uses new selector

Reconstruct data

Filter final state
Make THSParticles

Calc. Var.s
Filter
New tree

Qvalue
New tree

sWeights
New Tree

Use Weights Histories

Merge Weights With particle tree

Calculated Var.s
Explore data histograms

Code automatically generated for each step. Users fill in details.

Physics
Developed Mike Williams (CMU) for CLAS analysis
Look for N nearest events in kinematic space
Fit discriminatory variable for signal and back.
e.g. missing mass
Qval = S/(S+B)
Qval can then be used to weight events

HASPECT
*Selector class inherits additional Qvalue class
*Use RooFit event-by-event maximum likelihood
*Near. Neigh. saved
*Limit NN search with TEntryList
Given discriminatory PDF for signal and background calculates weight:

\[ sP_n(y_e) = \frac{\sum_{j=1}^{N_s} V n_j f_j(y_e)}{\sum_{k=1}^{N_s} N_k f_k(y_e)} \]

\( N_s \) = Number of species
\( f_k \) = PDF for species k
\( N_k \) = Yield for species k
\( V \) = covariance matrix

Part of RooStats (used here)
Can include multiple signal and background species

Can fit multidimensional discriminatory PDF
Test on “perfect” data (simulation)

Discriminatory variable M1
Signal Gaus(0,0.002)  Background Linear

Weighted variable M2
Signal Gaus(0,0.0035)  Background Flat

sWeights correctly reproduces M2 signal and background shape and uncertainties
Example CLAS Analysis

\[ \gamma p \rightarrow f_1(1285) \ p \rightarrow \pi^+\pi^- (\eta) p \]

Goal: Fit Veneziano (B4) amplitude to 3 meson decay

(Alessandro Rizzo)

Clear \( f_1 \rightarrow \pi a_0(980) \)

Dalitz unweighted

Dalitz sWeighted
Example 3–3.8GeV $\gamma p \rightarrow K^+K^-p$ CLAS g11 dataset

Van Hove Plots (Longitudinal)

\[ p_{K^+L} = \sqrt{\frac{2}{3}}q \sin \omega, \]
\[ p_{K^-L} = \sqrt{\frac{2}{3}}q \sin \left(\frac{2}{3} \pi + \omega\right), \]
\[ p_{PL} = \sqrt{\frac{2}{3}}q \sin \left(\frac{4}{3} \pi + \omega\right). \]
Example $\gamma p \rightarrow K^+K^-p$ at around 3-3.8 GeV
Larger Mass 2K mesons will have lower CM momenta.
Decay products can decay back into different sector.

Phase Space Plots:

Acceptance for increasing meson mass

For K+K- forward

Correlation of $\cos\theta_{GJ}$ and $\omega$ with $M_{K+K-} = 1.1$ and $M_{K+K-} = 1.6$

Meson X mass versus $E_g$ for valid LPS

For K+K- forward

$\beta_{CM} < \beta_{Meson}$

$M(2K) = 1-1.2$ OK, but...

$M(2K) > 1.2$ has limited $\theta_{GJ}$
Monte-Carlo Sampling of likelihood

Minuit Maximum Likelihood
- Single solution
  - We often have local maxima
  - How to choose initial parameters?
  - How to judge goodness of fit?
  - Implement Occam's Razor?

MCMC
- Samples full likelihood
- Not very efficient sampling
- Only finds unimodal solution
- Difficult to calculate evidence

Nested Sampling for General Bayesian Computation —
- J. Skilling, 2006, *International Society for Bayesian Analysis*
  - More efficient sampling
  - Intrinsically calculates evidence
  - model selection via Bayes factor
  - +Occams Razer

MultiNest
- Finds many maxima and the evidence for each
Bayesian Statistics is used for parameter estimation and hypothesis testing.

\[ \text{Likelihood} \times \text{Prior} = \text{Evidence} \times \text{Posterior} \]

\[ P(D|\theta, H) \times P(\theta|H) = P(D|H) \times P(\theta|D, H) \]

\[ L(\theta) \times \pi(\theta)d\theta = Z \times p(\theta)d\theta \]

Where \( D \) is the data set, \( \theta \) is a parameter vector, \( H \) is a model and

\[ \text{Evidence} = Z = \int L(\theta)\pi(\theta)\,d\theta \]

Likelihood integrated over the prior distribution.
Nested Sampling estimates evidence and finds likelihood maxima.

Define accumulated mass

Evidence can be evaluated as a 1D integral of likelihood over the prior accumulated mass

N “live points” maintained and one with lowest likelihood is replaced
Nested Sampling procedure involves points exploring the likelihood.

Note that only one new point needs to be calculated at each iteration, the $N$ points at iteration $i$ are the active live points.

Rejected points are kept to give the posterior distribution (All samples)
MultiNest in IU AmpTools

Calculate Intensity in terms of production and decay amplitudes

- Kinematics derived from 4-vectors
- Decay amplitudes (from theory)
- Incoherent sum
- Coherent sum
- Production amplitudes (complex fit parameters)

Constructed by user

Minimise:

\[-2 \ln L = -2 \sum_{i=1}^{N_{\text{observed}}} \ln(I'(\Omega_i)) + \frac{2}{N_{\text{MC generated}}} \sum_{i=1}^{N_{\text{MC accepted}}} I'(\Omega_i)\]
AmpTools Dalitz Tutorial

\[ X(3000) \rightarrow P_1(200)P_2(200)P_3(200) \]

Amplitude \( A_{\alpha\beta} \): Breit–Wigner

Isobars in \( P_1P_2 \) and \( P_1P_3 \)

Fit "prod, Amps" \( V_{\alpha\beta} \)

Minuit result in 0.03s

2800 generated data events
http://www.nuclear.gla.ac.uk/~dglazier/multinest/Dalitz1.mov
MultiNest Dalitz Fit, Posterior and Live Points

R12 Real V R12 Imag.

FitPars

Entries 14165
Mean x 0.72862
Mean y -0.04646
RMS x 35.63
RMS y 4.902

R12 Real V R13 Real

FitPars

Entries 14165
Mean x 0.72862
Mean y 1.03
RMS x 35.63
RMS y 35.02

Live R12 Real V R12 Imag.

FitLive

Entries 1000
Mean x 0.2433
Mean y -0.03697
RMS x 30.98
RMS y 3.093

Live R12 Real V R13 Real

FitLive

Entries 1000
Mean x 0.2433
Mean y 0.241
RMS x 30.98
RMS y 30.64
MultiNest Dalitz Fit

- 2 solutions, Evolution with iteration number

Mode 1

Re R12 = 30.96 ± 0.34
Re R13 = 30.64 ± 0.32
Im R13 = 3.03 ± 1.33

Mode 2

Re R12 = -30.96 ± 0.35
Re R13 = -30.64 ± 0.32
Im R13 = 2.94 ± 1.30

CPU time for 100 Live Points = 0.7s
Start with a simple case $\pi N \rightarrow \pi N$

**Helicity Amplitudes and partial waves**

\[
g(z) = \frac{1}{k^2} \sum_L \left[ (L + 1) T^+_L + LT^-_L \right] P_L(z)
\]

\[
h(z) = \frac{1}{k^2} \sum_L \left[ T^+_L - T^-_L \right] \sqrt{1 - z^2} P'_L(z)
\]

Use SAID PW

At 200 MeV

\[
\cos(\theta)
\]

Minuit Fit starting with correct parameters

\[
\Phi
\]

\[
\pi^+ p d\sigma/d\Omega \text{ from SAID multipoles } L_{\text{max}}=2
\]

\[
\pi^+ p P \text{ from SAID multipoles } L_{\text{max}}=2
\]
Truncate $L_{\text{max}} = 1$

$\text{PW : } S_1, P_1, P_3$

Colours indicate different "solutions"

~10,000 live points

~2 hours
Use Minuit with Random initial values

Lack of solutions where parameter close to 1

4000 fits ~ 3.5 hours (1s a fit)
~ 2M likelihood calculations
Fix S1 parameters to true value

MultiNest finds:

S1 $-0.256 \pm 0.003$ $-0.257$

Physical solution

P3 $-0.123 \pm 0.038$ $-0.126$

P1 $-0.091 \pm 0.001$ $-0.091$
Relative Partial Waves

Look at P3 phase relative to S1

Left with 6 discrete ambiguities
Summary

CLAS12 experiment will soon produce mesons through Quasi-real photoproduction

Currently preparing analysis framework to
  Handle large statistics datasets
  Analyse many final states
  Provide alternative methods

Investigated different signal/background separation

Investigated effectiveness of Longitudinal P.S.

Implemented Nested Sampling algorithm into AmpTools
  Investigating its usefulness in Amplitude Analysis

Currently implementing amplitudes in collaboration with JPAC and testing on available CLAS data
In general greater overlap between different experiments and theorists
Detect electrons at small angle to perform quasi-real photo-production experiments.

**Calorimeter:** electron energy/momentum
Photon energy (ν=E-E')
Polarization \( \varepsilon^{-1} \approx 1 + \nu^2/2EE' \)
PbWO\(_4\) crystals with APD/SiPM readout

**Scintillation Hodoscope:** veto for photons
Scintillator tiles with WLS readout

**Tracker:** electron angles, polarization plane
MicroMegas detectors

| \( E_{\text{scattered}} \) | 0.5 - 4.5 GeV |
| \( \theta \) | 2.5\(^\circ\) - 4.5\(^\circ\) |
| \( \phi \) | 0\(^\circ\) - 360\(^\circ\) |
| \( \nu \) | 6.5 - 10.5 GeV |
| \( Q^2 \) | 0.01 - 0.3 GeV\(^2\) \( (< Q^2 > 0.1 \text{ GeV}^2) \) |
| \( W \) | 3.6 - 4.5 GeV |
CLAS12 Detector Systems

**Forward Detector**
- TORUS Magnet
- Forward silicon vertex tracker
- HThresh Cerenkov Counter
- LThresh Cerenkov Counter
- Forward TOF System
- Preshower calorimeter
- E.M. Calorimeter

**Central Detector**
- SOLENOID magnet
- Barrel silicon tracker
- Central TOF

**Additional Equipment**
- Micromegas (CD)
- Neutron detector (CD)
- Forward RICH
- Forward Tagger

Enable e- detection below 5° Ready for data Summer 2017
Qvalue with fixed (true) signal width

- \( c_0 = 0.027 \pm 0.391 \)
- \( f_{BckYield} = 19.81 \pm 6.14 \)
- \( f_{SigYield} = 80.17 \pm 9.87 \)
- \( \text{sigmean} = 0.000 \)
- \( \text{sigwidth} = 0.002 \)

Global Fit parameters:

- \( \text{RMS} = 0.00316 \pm 0.00022 \)
- \( \text{Mean} = -0.000009 \pm 0.000032 \)
- \( \text{Entries} = 100 \)

Qvalue reproduces signal and background shape
But uncertainties not correct (need to calculate)
And if width not constrained ...